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Grain refinement of 1050 aluminum alloy by friction stir processing

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In the last ten years, friction stir welding (FSW) has emerged as a new solid state joining technique [1], especially for aluminum alloys [2–8]. In this processing, a rotating tool travels down the length of contacting metal plates, and produces a highly plastically deformed zone through the associated stirring action. The localized heating is produced by friction between the tool shoulder and the plate top surface, as well as plastic deformation of the material in contact with a tool [1]. This processing results in a stirred zone with very fine grain size even in a single pass [9, 10]. Recently, Benavides *et al.* [9] have examined the FSW of 2024 aluminum alloy at temperatures from room temperature (about 303 K) to 173 K prior to the start of the FSW process. They have reported that the size of the grains is less than 0.8 μm when FSW is started at 173 K. On the other hand, Mishira *et al.* [10] have reported that the grains of about 3 μm was obtained for 7075 aluminum alloy by using FSW. They have named this processing friction stir processing (FSP). The results mentioned above suggest a possibility to apply FSP technique to produce fine-grained metallic materials.

In the present paper, we will report the production of fine-grained 1050 aluminum alloy (commercially pure aluminum) by using FSP technique. In addition, we will report that the microstructure of the base metal has an effect on the microstructure of the FSP zone. The alloy selected was 5 mm thick commercial 1050 aluminum alloy plate (nominally 99.5 mass% Al, 0.25 mass% Si, 0.4 mass% Fe, 0.05 mass% Cu, 0.05 mass% Mn, 0.05 mass% Mg). The rolled plates and the annealed plates were used for FSP so as to investigate the effect of the base metal microstructure on the microstructure of the friction stir processed sample. Annealing was conducted at 693 K for 18 ks. The tool rotation speed and the welding speed were 1540 rpm and about 0.5 mm/s, respectively. Schematic illustration of FSP is shown in Fig. 1. Following FSP, microstructures of the samples were observed by both optical microscopy and transmission electron microscopy (TEM). Vickers microhardness profiles were measured on the cross section perpendicular to the welding direction.

Fig. 2 shows the optical micrographs of the rolled sample and the annealed sample after FSP. In each sample, FSP zone can be clearly distinguished from the base metal. That is, FSP zone of the rolled sample consists of the fine grains although the base metal shows elongated grains to the rolling direction. In contrast to the rolled sample, the base metal of the annealed sample consists of equiaxed grains of 30–40 μm. Although the FSP zone of this sample consists of equiaxed grains, the grain size is smaller in the FSP zone than in the base metal. The detailed observation of the microstructure will be shown in Figs 3 and 4.

Fig. 3 shows the result of TEM observation of the rolled sample. In the base metal (Fig. 3a), there are many dislocations and subgrains inside the grains that elongate to the rolling direction. In contrast to the base metal, recrystallized grains of about 1–2 μm are seen in the FSP zone (Fig. 3b). It is noteworthy that a stirred zone with very fine grain size can be obtained even in a single pass of processing. That is, FSP can be a useful processing to produce fine-grained 1050 aluminum alloy.

Fig. 4 shows the results of TEM observation of the annealed sample. As shown in Fig. 4a, dislocation density is very low in the base metal. FSP zone of the annealed sample (Fig. 4b), like that of the rolled sample,

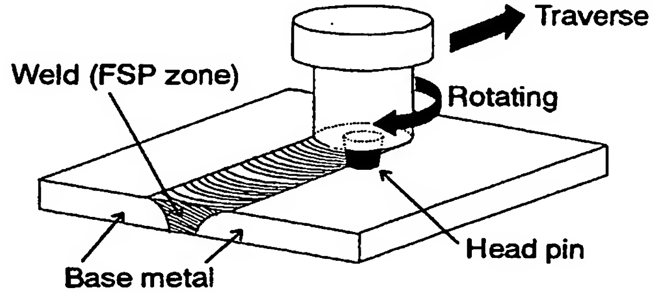

Figure 1 Schematic illustration of friction stir processing (FSP).

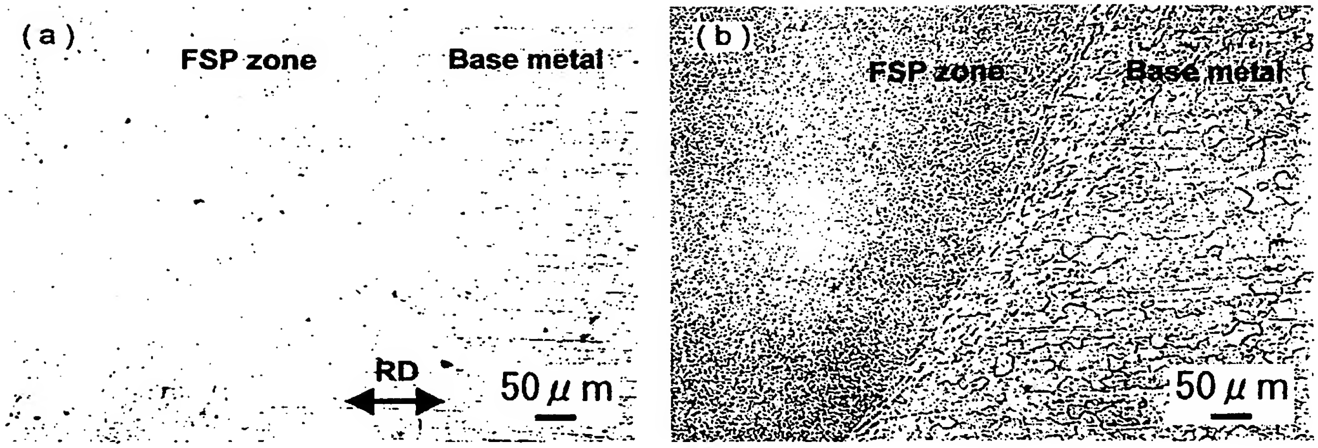

Figure 2 Optical micrographs of the friction stir processed 1050 aluminum alloy. (a) and (b) show the results of the rolled sample and the annealed sample, respectively. RD denotes the rolling direction of the sample.

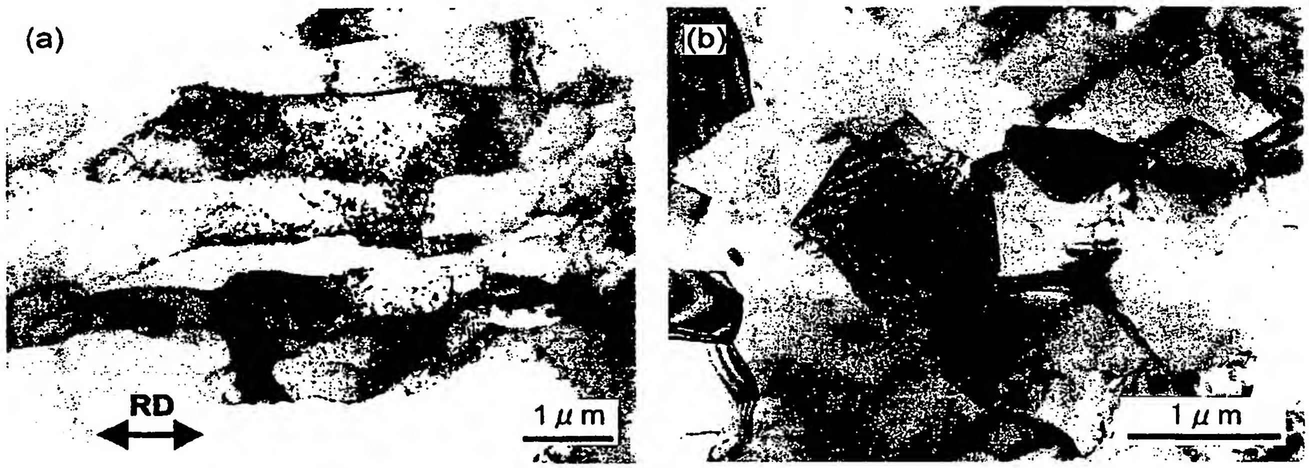

Figure 3 Transmission electron micrographs of the rolled 1050 aluminum alloy. (a) and (b) show the microstructures of the base metal and the friction stir processed zone, respectively. RD denotes the rolling direction of the sample.

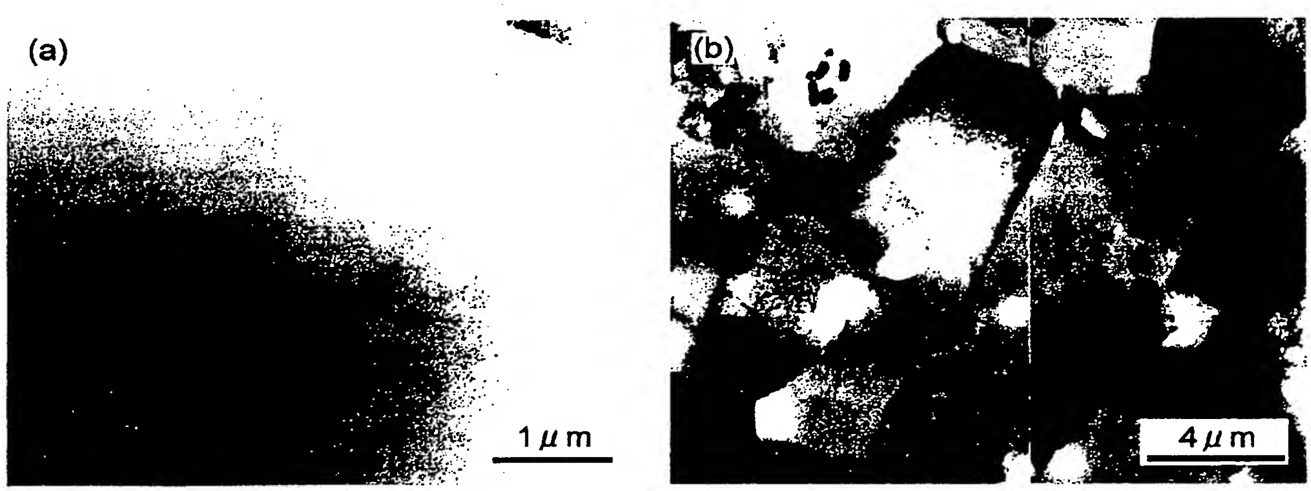

Figure 4 Transmission electron micrographs of the annealed 1050 aluminum alloy. (a) and (b) show the microstructures of the base metal and the friction stir processed zone, respectively.

consists of fine recrystallized grains of 4–8 μm that is slightly larger than that of the rolled sample. That is, it seems that the gain size of the FSP zone depends on the microstructure of the base metal. Although the detailed discussion cannot be made now, that the gain size of the FSP zone depends on the prior microstructure of the sample suggests the possibility to control the grain size of the FSP zone.

As stated above, FSP can produce fine-grained 1050 aluminum alloy (commercially pure aluminum). On the other hand, it has been reported that fine-grained pure aluminum can be produced by using severe plastic

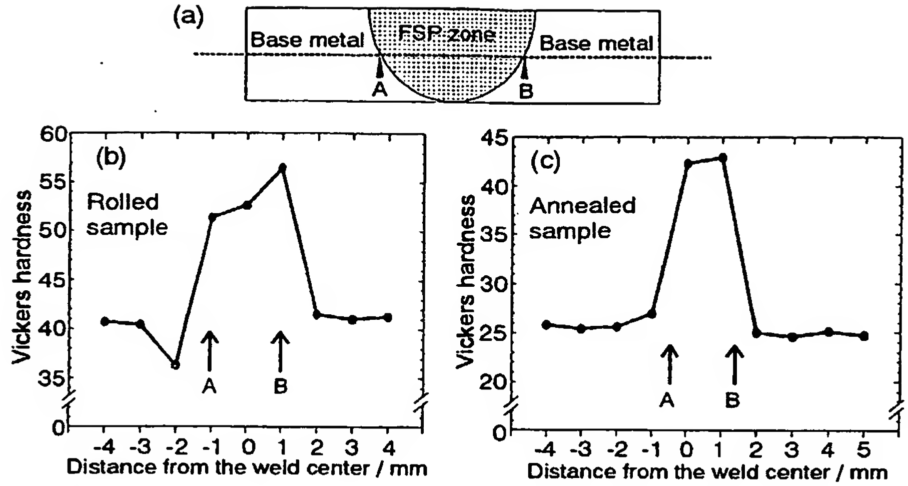

Figure 5 Vickers microhardness traverse across the friction stir processed zone along the broken line on the cross section schematically shown in (a). (b) and (c) show the results of the rolled 1050 aluminum alloy and the annealed 1050 aluminum alloy, respectively.

deformation processing [11, 12]. Iwahashi *et al.* [11] has examined the microstructure of 99.99% aluminum during equal channel angular pressing (ECAP). They have reported that equiaxed ultra-fine grain size of about 1 μm was obtained after 10 pressing. Saito *et al.* [12] has examined the microstructure of 1100 aluminum alloy (commercially pure aluminum) during accumulative roll-bonding (ARB). They have reported that the fine-grained 1100 aluminum alloy with mean grain size of 670 nm was produced after ARB of 8 cycles at 473 K. Although using these severe plastic deformation processing can produce fine-grained pure aluminum, multiple pass of processing is needed to do so. In contrast to these processing, however, FSP can produce fine-grained commercially pure aluminum in a single pass of processing. Hence, it is concluded that FSP can be a useful processing to produce fine-grained aluminum alloy.

Fig. 5 shows the microhardness along the centerlines of both the rolled sample and the annealed one after FSP. It is apparent that the FSP zone is significantly harder than the base metal in each sample. The sample used in the present research (1050 aluminum alloy) is the alloy without age hardening. Thus, hardness depends on both the grain size and the dislocation density. In each sample, the grain size is smaller in the FSP zone than in the base metal. Dislocation density is lower in the FSP zone than in the base metal for the rolled sample. Hence, the small grain size may be attributed to the higher hardness in the FSP zone than in the base metal for the rolled sample. For the annealed sample, as shown in Fig. 4b, dislocation density is higher in the FSP zone than in the base metal. Hence, the small grain size and the dislocations may be attributed to the higher hardness in the FSP zone than in the base metal for the annealed one. In addition, as shown in Fig. 5, maximum hardness value in the FSP zone is higher in the rolled sample than in the annealed one. This may also be due to the difference of the grain size between the samples.

In conclusion, following results were obtained.

(1) FSP can produce fine-grained 1050 aluminum alloy. For example, the grain size in the FSP zone is 1–2 μm and 4–8 μm for the rolled sample and the annealed sample, respectively.

(2) The grain size in the FSP zone depends on the condition of the base metal, e.g. the rolled sample and the annealed sample.

(3) Microhardness value of the sample is higher in the FSP zone than in the base metal. This may be due to the smaller grain size and/or the higher dislocation density in the FSP zone.

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